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CONTROL OF CYLINDER TEMPERATURES BY THERMOSTATICALLY OPERATED INTERNAL-COOLANT VALVES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

CONTROL OF CYLINDER TEMPERATURES BY THERMOSTATICALLY OPERATED INTERNAL-COOLANT VALVES

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SUMMARY

Tests were conducted to determine the performance of automatic, internal-coolant valves actuated by cylinder temperatures. Two thermostatically operated internal-coolant valves were tested on a cylinder from a radial air-cooled engine with a 3350-cubic-inch displacement and on a cylinder from a radial air-cooled engine with a 2800-cubic-inch displacement in single-cylinder tests to determine the performance with respect to temperature sensitivity, rapidity of response, and hunting characteristics. Data were also obtained to indicate the relative effects on cylinder performance obtained by internally supplying water and additional fuel.

The results indicated that the two thermostatically operated valves provided accurate control of temperatures at the control points when either water or fuel was used as an internal coolant. Valve response was sufficient to offset normal rates of temperature rise but was insufficient to prevent the extremely rapid rates of temperature rise accompanying severe preignition. The hunting exhibited by the two thermostatically operated coolant valves was not excessive provided that the available flow capacity was held within the limits required at any one intake pressure. Water was ineffective in cooling the exhaust-valve guides and the exhaust-valve seats. The temperature of the rear spark-plug bushing provided a reliable index of cylinder temperatures when cooling was altered by varying the fuel-mixture strength but provided an unreliable index of cylinder temperatures when cooling was varied with water as an internal coolant.

INTRODUCTION

In a previous analysis of the temperature and the fuel-air distribution of four radial aircraft engines (reference 1), substantial reductions in fuel consumption were obtained by adding water or fuel to only the overheated cylinders in air-cooled aircraft-engine installations in which overheating is customarily prevented by enriching the fuel-air mixture to the entire engine.

As a part of the general program requested by the Air Technical Service Command, Army Air Forces, to improve the cooling of the R-3350 engine, an investigation of the means of improving the cylinder-to-cylinder temperature distribution of this engine was conducted at the NACA Cleveland laboratory during the early part of 1945. Single-cylinder tests were conducted on cylinders from two radial air-cooled engines to determine the performance of two thermostatically operated coolant valves designed to supply coolant as required by the individual engine cylinders. The results of these tests are presented herein.

The tests were specifically made to determine the performance of two simple, direct-acting, thermostatically operated coolant valves with respect to temperature sensitivity, rapidity of response, and hunting characteristics. A secondary object of these tests was to demonstrate the effects on cylinder performance of internally supplying water and additional fuel.

CHOICE OF COOLANT

Unpublished data taken on a single cylinder of a 12-cylinder liquid-cooled engine indicate (fig. 1) the relative effectiveness of gasoline, water, and a 50-percent water-ethanol mixture in cooling the exhaust valve when the coolant is added at basic fuel-air ratios of 0.060 and 0.085. From figure 1 it is evident that water is the most economical of the three coolants on the lean side of the mixture-temperature peak when only a small amount of cooling is required. Gasoline is the most economical, however, when large amounts of cooling are necessary and the water-ethanol mixture is the least economical on the lean side of the peak regardless of the amount of cooling required. For cooling the exhaust valve at the rich mixtures, gasoline is the most economical with little choice between water and the water-ethanol mixture.

The chief advantage of water or water-ethanol as a coolant at rich mixtures is the possibility of using greater quantities than is feasible with gasoline. In this matter, the temperature-limited and the knock-limited power range can be extended.

The unsatisfactory lean-mixture characteristics of the water-ethanol mixture as shown in figure 1 precluded it as a coolant in the tests of the two cylinders.

APPARATUS AND TEST CONDITIONS

Coolant valves. - The two thermostatically operated coolant valves tested (valves A and B) are shown in figure 2. Both valves are of the liquid-expansion type with liquid-expansion chambers located at some temperature-responsive point on the cylinder. The liquid-expansion chambers of both valves were filled with dibutyl phthalate, which is a colorless, odorless, oily, organic compound having a specific gravity of 1.048, a boiling point of 643° F, and a pour point of approximately -69° F. The coefficient of cubical expansion is 0.00042 per °F.

The expansion chamber of valve A was incorporated in the spark-plug gasket. This valve was tested on rear-row cylinder I (from a radial air-cooled engine with a 3350-cubic-inch displacement) with the expansion chamber located at the rear spark plug and the injection nozzle mounted on the intake pipe (about 16 in. from the cylinder port) for injection of coolant.

The expansion chamber of valve B was designed to screw into a hole in the cylinder head. In the tests described herein, this chamber was mounted in the front spark-plug hole of front-row cylinder II (from a radial air-cooled engine with a 2800-cubic-inch displacement). The front spark plug was installed in an adjacent hole. The internal-coolant nozzle was screwed into the primer hole.

With both valves the internal coolant (water or fuel) was injected through an orifice; no attempt was made to secure atomization.

Engines. - The tests of valves A and B were conducted on separate CUE crankcases coupled to electric dynamometers. Injection pumps were used to supply the basic fuel. (Hereinafter the fuel used for normal operation will be designated basic fuel as distinguished from the additional fuel supplied from the thermostatically operated valve.) The basic fuel was injected into the induction system ahead of a vaporization tank.

Cooling air was supplied by a central air system through a duct 16 inches in diameter leading to a cowling box surrounding the cylinder. Standard engine baffles were used on the cylinders.

Instrumentation. - Temperatures on cylinder I were measured by 15 thermocouples located as shown in figure 3. Thermocouples on cylinder II were located in a similar manner except that none were installed around the exhaust-valve seat and an extra thermocouple was installed in the center of the head between the valves, 1/8 inch from the combustion chamber.

All water- and fuel-flow measurements were made with calibrated rotameters.

In both engine setups the difference between the static pressure in the cowling box before and after the cylinder was used as the cooling-air pressure drop Δp. Pressure-drop measurements were corrected to standard air density for the air in front of the cylinder by multiplying Δp the measured cooling-air pressure drop by σ the ratio of the dinsity of the air ahead of the cylinder to the standard air density of 0.0765 pound per cubic foot.

Test conditions. - The following engine conditions were maintained constant unless otherwise specified:

	Cylinder I	Cylinder II
Internal-coolant valve	A	B
Location of temperature control	Rear spark-plug gasket	Front spark-plug hole
Indicated horsepower	70	80
Engine speed, rpm	2000	2000
Fuel-air ratio	0.065	0.083
Inlet-air pressure, inches of mercury absolute	30	38
Inlet-air temperature, °F	150	150
Spark advance, degrees B.T.C.	20/20	20/20
Compression ratio	6.8	7.7
Cooling-air temperature, °F	80	65-85
Oil-in temperature, °F	185	185
Fuel	AN-F-28	AN-F-28

RESULTS AND DISCUSSION

Low-Power Cruise Tests

As indicated in the table of conditions, the tests on cylinder I were made with a basic fuel-air ratio of 0.065 (unless otherwise specified). This operation was intended to represent a low fuel-consumption cruise condition. Thermostatically operated valve A was used in these tests with the temperature-control point at the rear spark-plug gasket. The flow characteristics of valve A with respect to the temperature of the rear spark-plug bushing are shown in figure 4. These data were obtained on cylinder I with the valve supplying water or additional fuel as internal coolant. The reciprocal slopes of the curves of figure 4 are called valve sensitivities in this report and are expressed in pounds per hour per degree Fahrenheit.

Effect of varying basic fuel-air ratio. - The data of figure 5 demonstrated the performance of cylinder I and valve A when the basic fuel-air ratio was varied. The valve, which was set to open when the temperature of the rear spark-plug bushing reached approximately 402° F, satisfactorily controlled the bushing temperature with either water or fuel. At basic mixtures leaner than that for peak temperature, the power and the temperatures remained practically constant when fuel was supplied because the over-all fuel-air ratio was held approximately constant by the valve even though the basic fuel-air ratio was progressively reduced. As described in reference 1, a closing device, which would have closed the valve when the basic fuel-air ratio became so lean that no internal cooling was required, would have been advantageous.

The cylinder temperatures shown in figure 5 illustrate the relative ineffectiveness of water as a coolant when compared with fuel. With the controlled temperature at the rear spark-plug bushing, the water was of practically no value in cooling the exhaust-valve guide and was of limited value in cooling the exhaust-valve seat and front spark-plug bushing. Furthermore, these data illustrate how poorly the rear spark-plug bushing serves as a criterion of cylinder cooling when using water as an internal coolant. The temperature reductions obtained at the rear spark plug with fuel cooling were reflected in all cylinder temperatures.

Effect of varying cooling-air pressure. - Satisfactory control of the temperature of the rear spark-plug bushing was effected with valve A (fig. 6) when the cooling-air flow was varied. These data, obtained with a basic fuel-air ratio of 0.065, show that the rear spark-plug electrode was somewhat overcooled when water or fuel was used. Water was relatively ineffective in cooling the exhaust-valve guide and the exhaust-valve seat. Because the basic fuel-air ratio was on the lean side of the temperature peak, better liquid economy was obtained with water than with fuel.

Effect of varying inlet-air pressure. - The cylinder performance obtained when the inlet-air pressure was varied is shown in figure 7.

The controlled temperature was satisfactorily maintained by valve A. These data substantiate the general conclusions already presented regarding the relative ineffectiveness of water as a coolant for the exhaust-valve guide. The poor correlation of rear-spark-plug-bushing temperatures and internal cylinder temperatures when water is used as a coolant is again apparent.

Valve response and hunting characteristics. - The response of the cylinder and valve to a sudden change in the basic fuel-air mixture from 0.109 to 0.062 is shown in figure 8, which also presents information concerning the hunting characteristics of the valve at these conditions. In preliminary tests, the hunting characteristics were found to be unsatisfactory when the available coolant-flow capacity was much in excess of the required at any one intake pressure. When the coolant-pressure differential was manually limited to 2 pounds per square inch above the engine inlet-pipe pressure, excessive hunting was avoided.

High-Power Cruise Tests

High-power cruise tests were conducted with thermostatically operated valve B on cylinder II using the front spark-plug bushing as the controlled temperature. If not otherwise specified, the basic fuel-air ratio was 0.083. This ratio represents a high-power cruise, or climb, condition.

Effect of varying basic fuel-air ratio. - The results of the tests on cylinder II with varying basic fuel-air ratio (fig. 9) are somewhat similar to the results obtained with the 3350 cylinder (fig. 5). Valve B satisfactorily controlled the temperature of the front spark-plug bushing when both water and fuel were used. At basic mixtures leaner than that for peak temperature, the curve obtained with fuel as the coolant was similar to that of figure 5 because the basic fuel-air ratio was progressively reduced. Water was relatively ineffective in cooling the rear spark-plug electrode, the rear spark-plug bushing, and the exhaust-valve guide. The cooling of the rear spark-plug bushing as effected by the addition of fuel was again reliably reflected in all cylinder temperatures.

Effect of varying inlet-air pressure. - The results obtained by varying the inlet-air pressure at the high-power cruise condition as shown in figure 10 are similar to those obtained at the lean-cruising condition (fig. 7), except that the specific liquid consumption with fuel was slightly less than with water at the richer mixture of the high-power cruise condition. The reverse was true at the low-power mixture, which was leaner than the peak-temperature mixture. These data and those of figure 1 establish the conclusion that, in general, water is a more economical coolant than fuel at mixtures leaner than the peak-temperature mixture and fuel is more economical at mixtures richer than the peak-temperature mixture. The difference in economy depends on the particular cylinder temperature used as a reference.

Valve hunting characteristics and response to preignition. The response and hunting characteristics of valve B (fig. 11) were similar to those of valve A (fig. 8).

Supplementary tests with cylinder II were conducted under preigniting conditions to determine whether the valve response was sufficiently rapid to prevent damage from preignition. In these tests preignition was induced with a Champion 8CFR spark plug in the rear spark-plug bushing. The 8CFR spark plug was found to cause preignition when the cylinder operated with an inlet pressure of 36 inches of mercury absolute, a fuel-air ratio of 0.070, and a cooling-air pressure drop of 5.3 inches of water. Under these conditions preignition was encountered for 20 or 30 seconds before becoming sufficiently far advanced to cause a drop in torque. Little rise in cylinder temperature was observed until after the torque began to decrease. As a consequence, the valve responded too late to avoid severe and possible damaging preignition. Under closely regulated conditions, the valve could be set to provide coolant just after preignition began; in these cases preignition was stopped.

SUMMARY OF RESULTS

From the tests conducted with two thermostatically operated internal-coolant valves on a cylinder from a radial air-cooled engine with a 3350-cubic-inch displacement (cylinder I) and on a cylinder from a radial air-cooled engine with a 2800-cubic-inch displacement (cylinder II), the following results were obtained:

1. Both thermostatically operated coolant valves provided accurate control of temperatures at the control points when either water or fuel was used as an internal coolant.

2. The valve response was sufficient to offset normal rates of temperature rise but was insufficient to prevent the extremely rapid rates of temperature rise accompanying severe preignition.

3. The hunting exhibited by the two thermostatically operated coolant valves was not excessive provided that the available flow capacity was held within the limits required at any one intake pressure.

4. Water was ineffective in cooling the exhaust-valve guides and the exhaust-valve seats.

5. The temperature of the rear spark-plug bushing provided a reliable index of cylinder temperatures when cooling was altered by varying the fuel-mixture strength but provided an unreliable index of cylinder temperatures when cooling was varied with water as an internal coolant.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, July 16, 1945.

REFERENCE

1. Biermann, Arnold E., Miller, George R., and Henneberry, Hugh M.: Economy of Internally Cooling Only the Overheated Cylinders of Aircraft Engines. NACA MR No. E5G14, July 14, 1945.

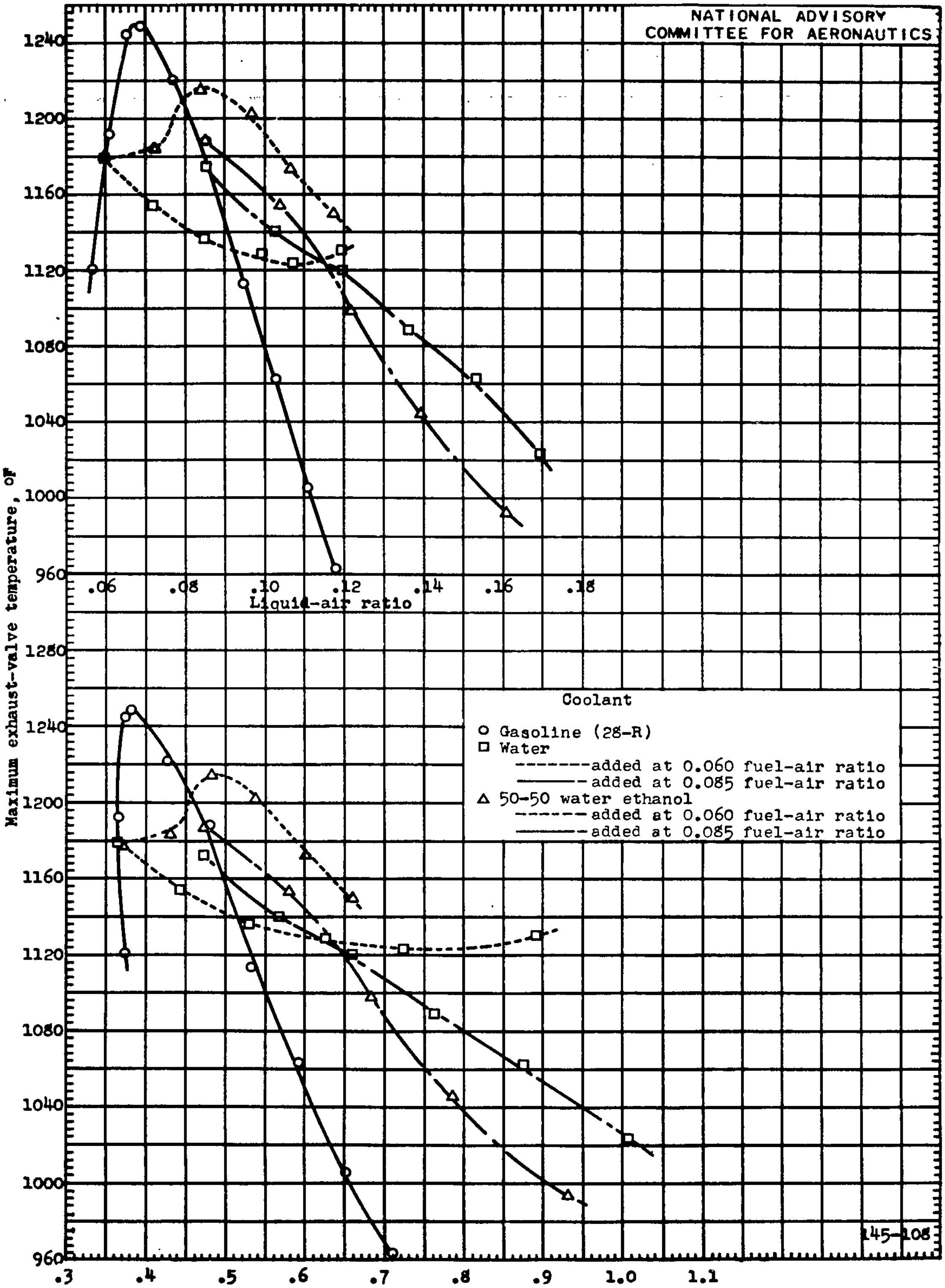
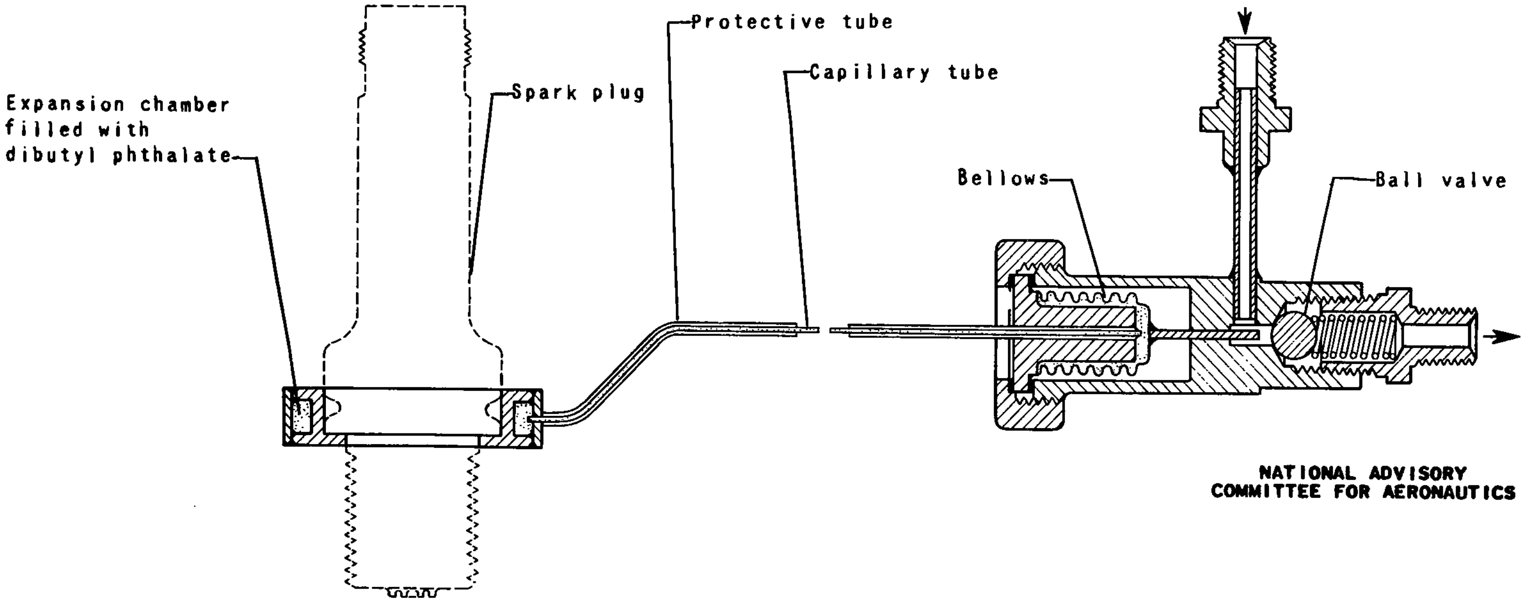
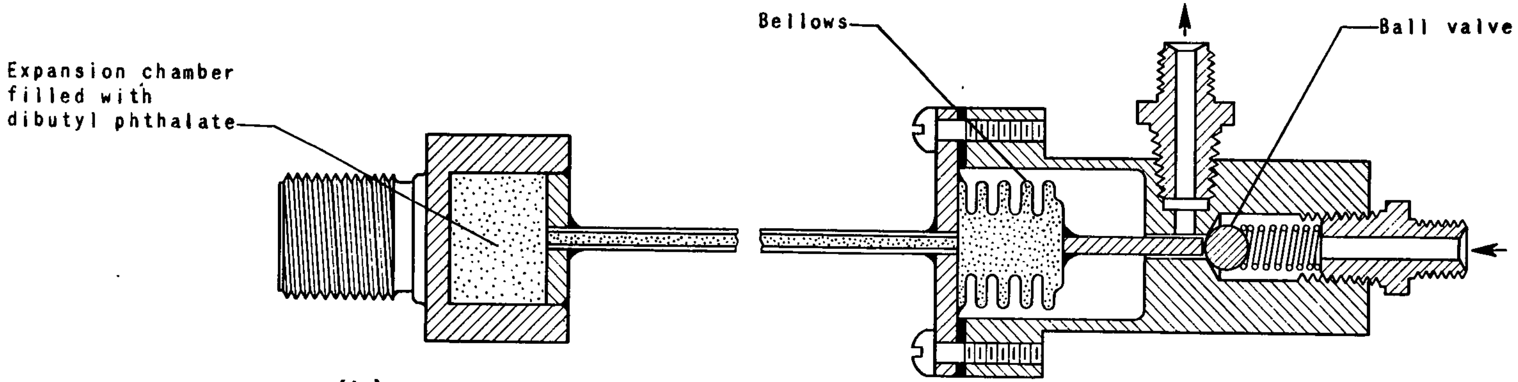


Figure 1. - Effect of coolant additions on exhaust-valve temperatures at basic fuel-air ratios of 0.060 and 0.085. Liquid-cooled single cylinder; indicated horsepower, 94; engine speed, 2600 rpm; indicated mean effective pressure, 200 pounds per square inch; inlet-air temperature, 265° F; spark advance: inlet, 28° B.T.C.; outlet, 34° B.T.C.



(a) Valve A, cylinder I.



(b) Valve B, cylinder II.

Figure 2. - Sectional views of coolant valves used on cylinders I and II.

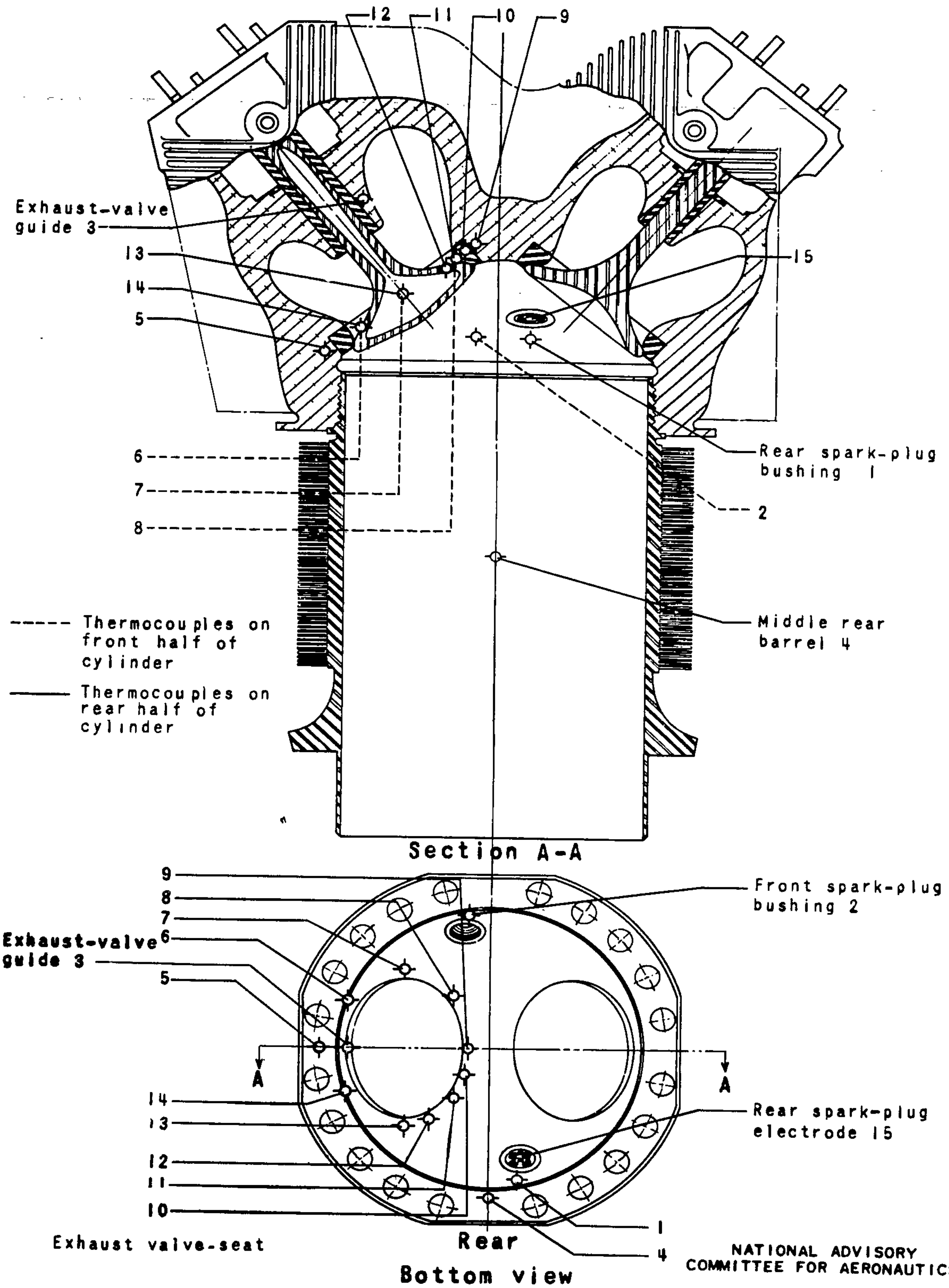


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Figure 3. - Location of thermocouples in cylinder I.

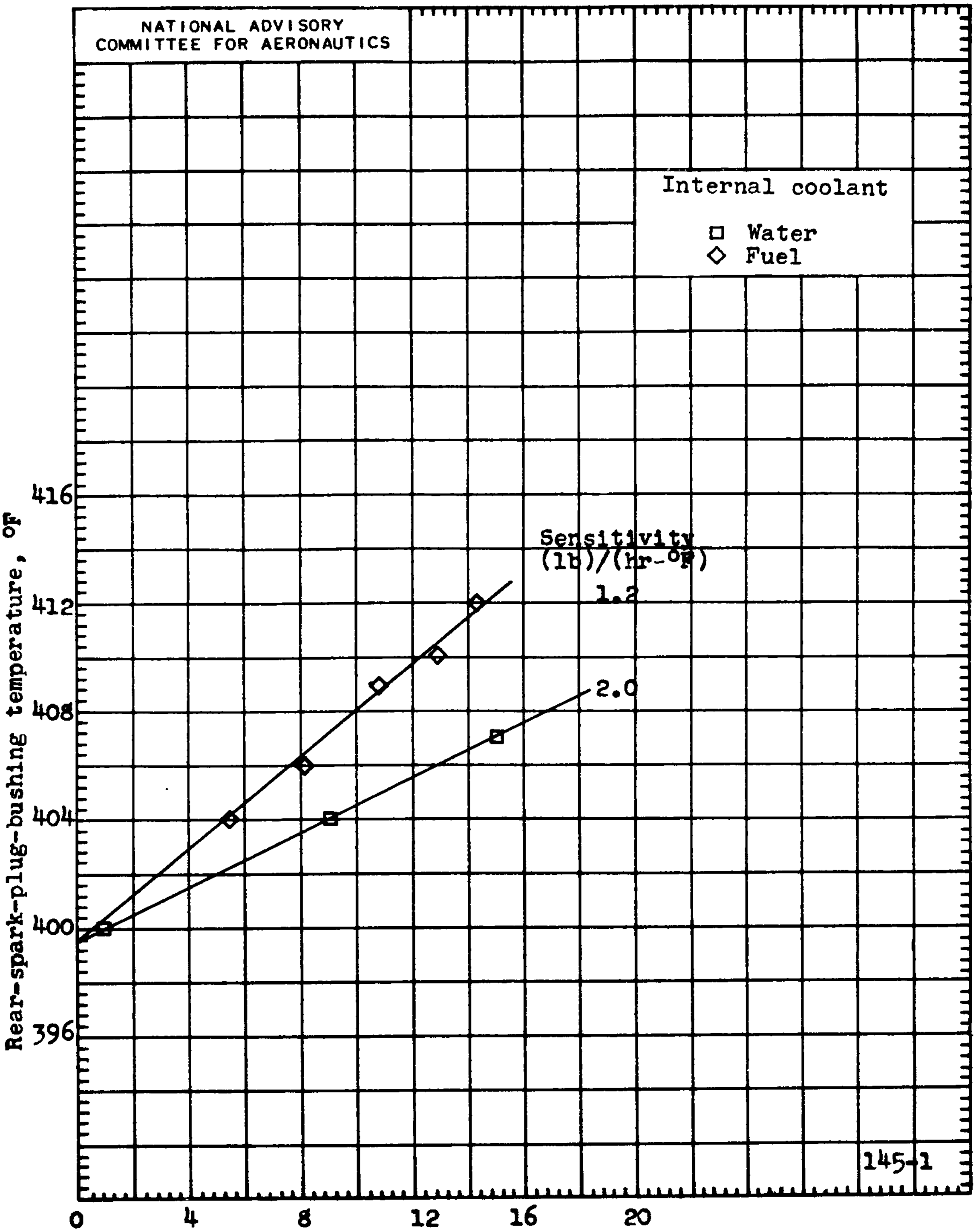


Figure 4. - Flow characteristics of thermostatically operated valve A with water and fuel in cylinder I.

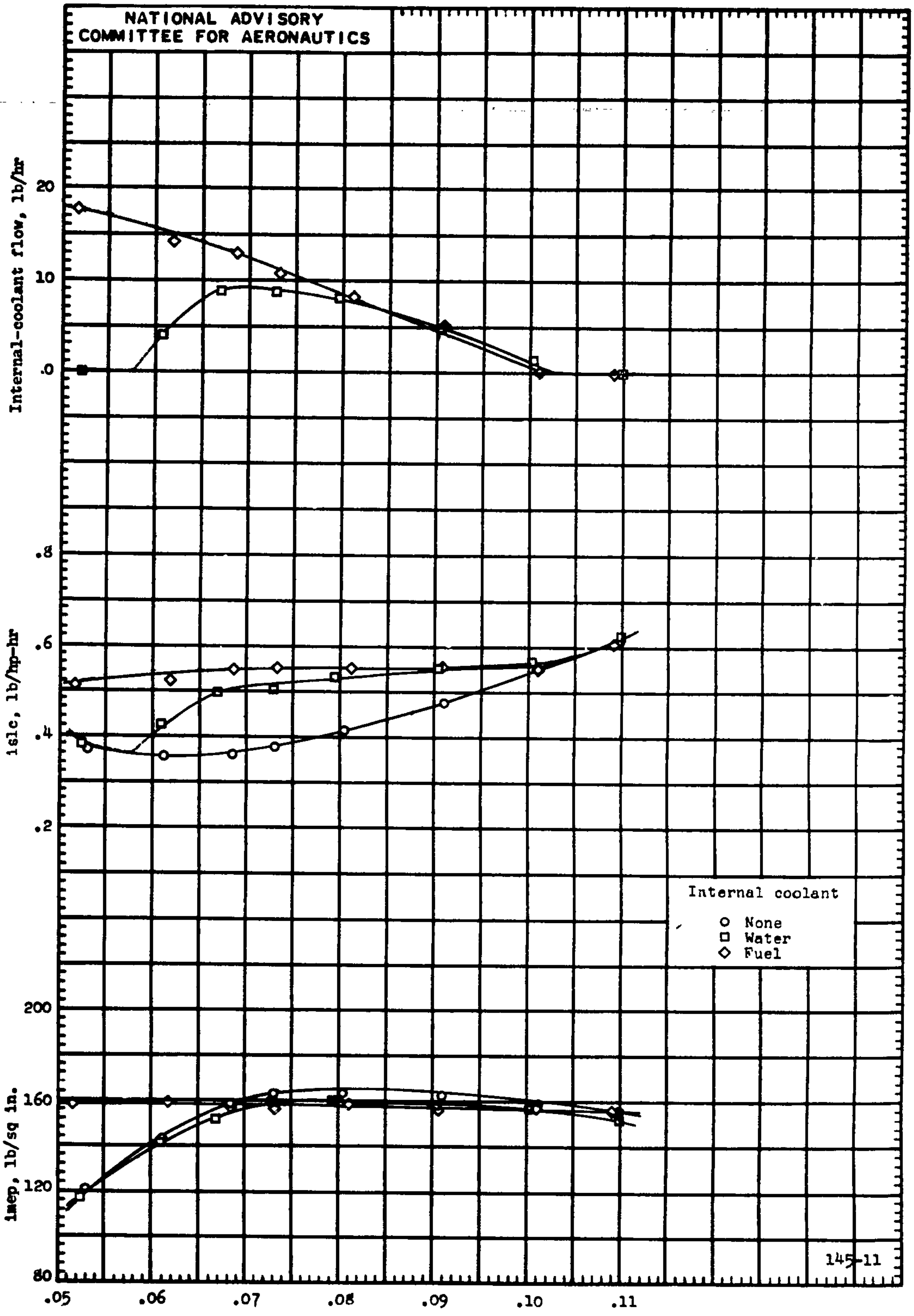


Figure 5. - Effect of basic fuel-air ratio on performance of cylinder I equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spark-plug-bushing temperature. Engine speed, 2000 rpm; inlet-air pressure, 30 inches mercury absolute; inlet-air temperature, 150° F.

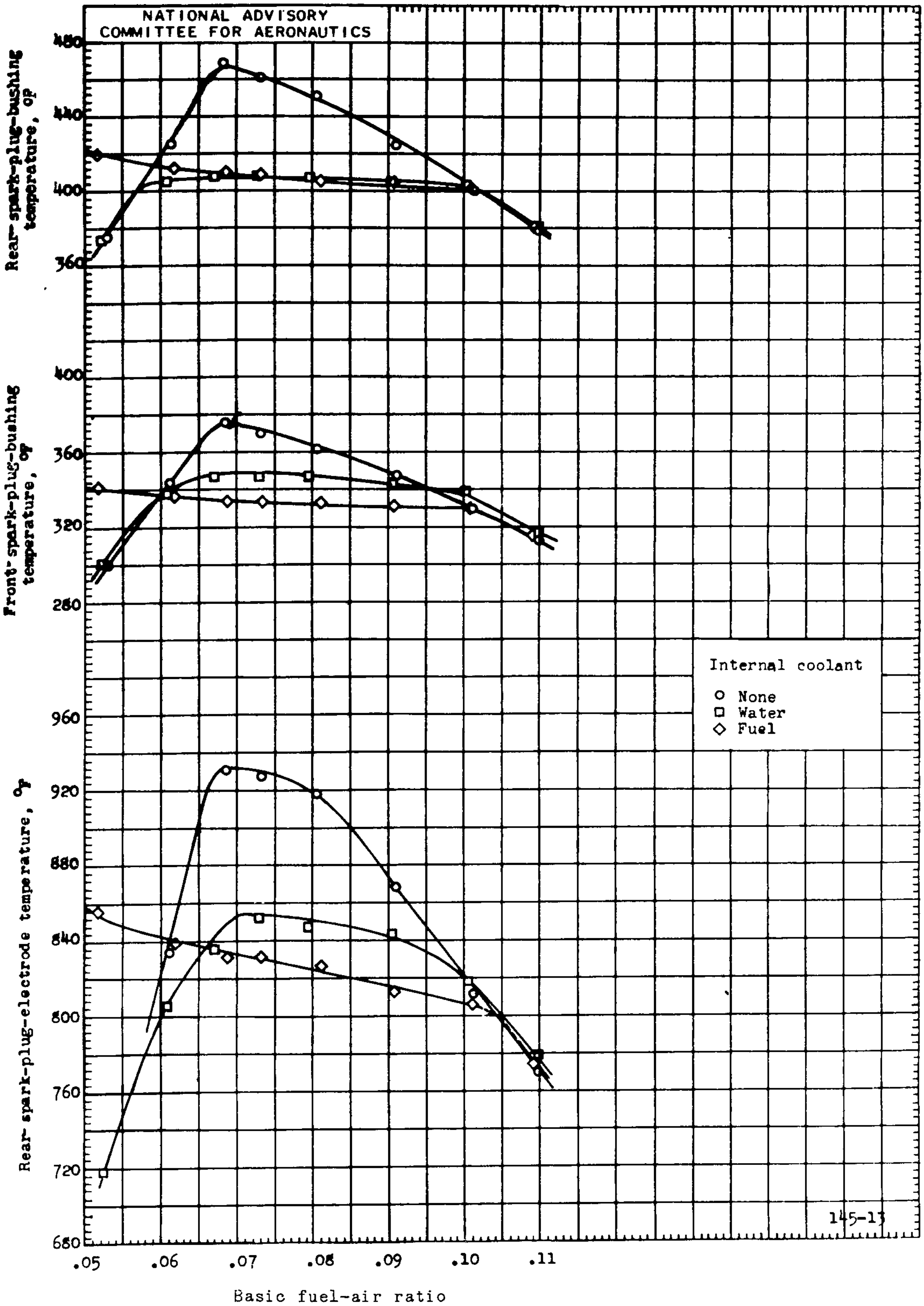


Figure 5. - Continued. Effect of basic fuel-air ratio on performance of cylinder I equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spark-plug-bushing temperature, Engine speed, 2000 rpm; inlet-air pressure, 30 inches mercury absolute; inlet-air temperature, 150° F.

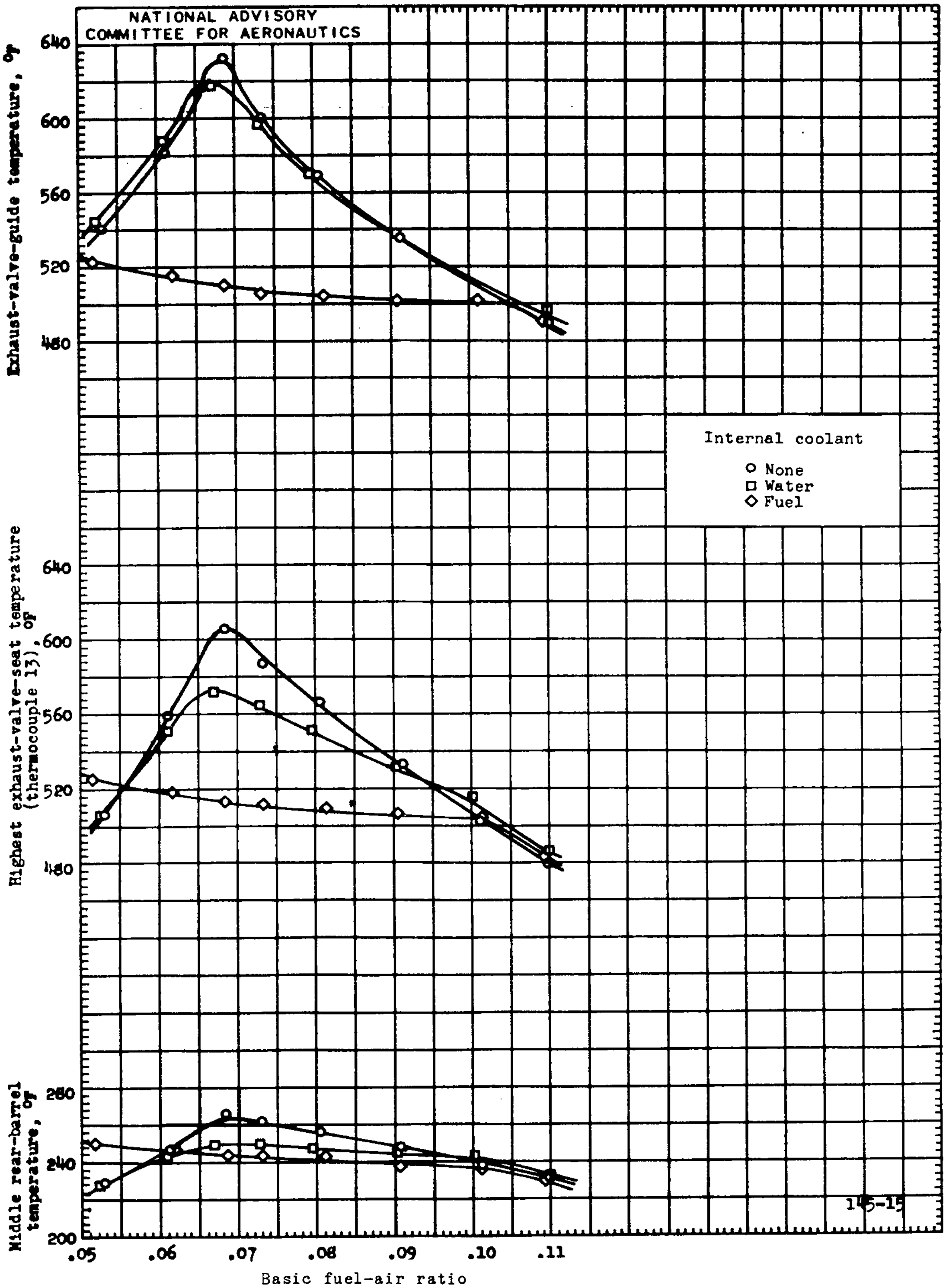


Figure 5. - Concluded. Effect of basic fuel-air ratio on performance of cylinder I equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spark-plug-bushing temperature. Engine speed, 2000 rpm; inlet-air pressure, 30 inches mercury absolute; inlet-air temperature, 160° F.

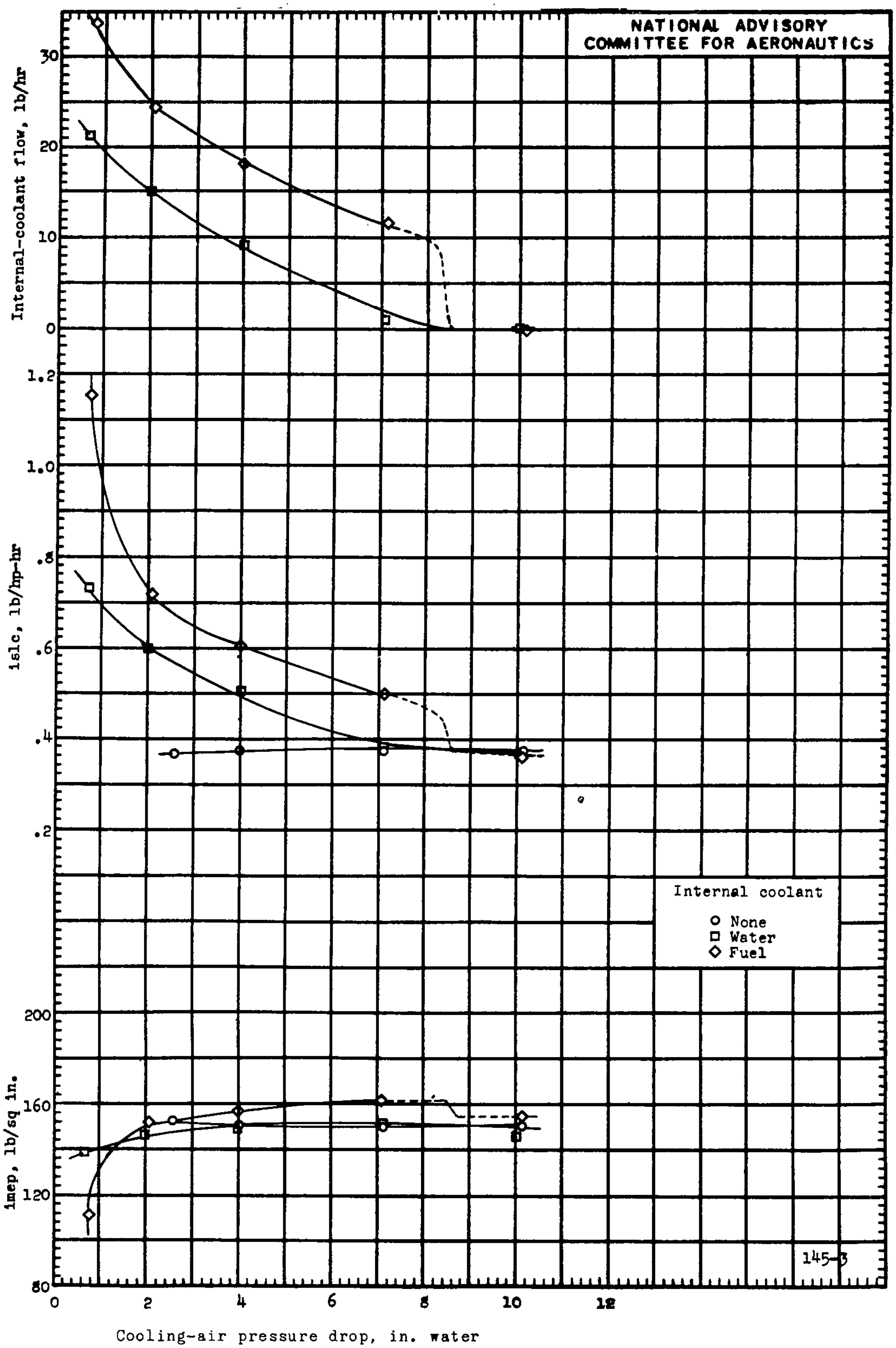


Figure 6. - Effect of cooling-air pressure drop on performance of cylinder I equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spark-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.065; inlet-air pressure, 30 inches mercury absolute; inlet-air temperature, 150° F.

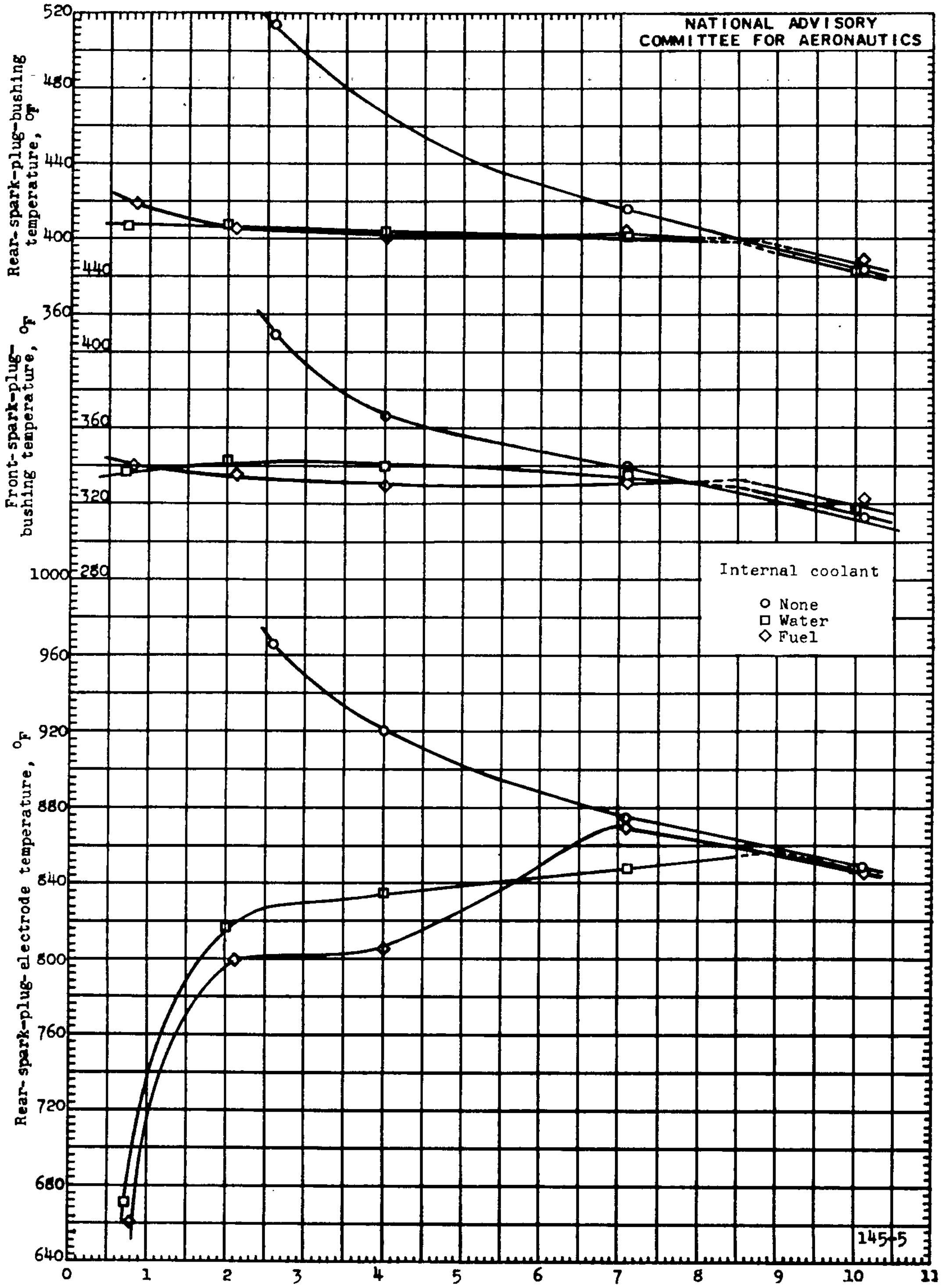


Figure 6. - Continued. Effect of cooling-air pressure drop on performance of cylinder I equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spark-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.065; inlet-air pressure, 30 inches mercury absolute; inlet-air temperature, 150° F.

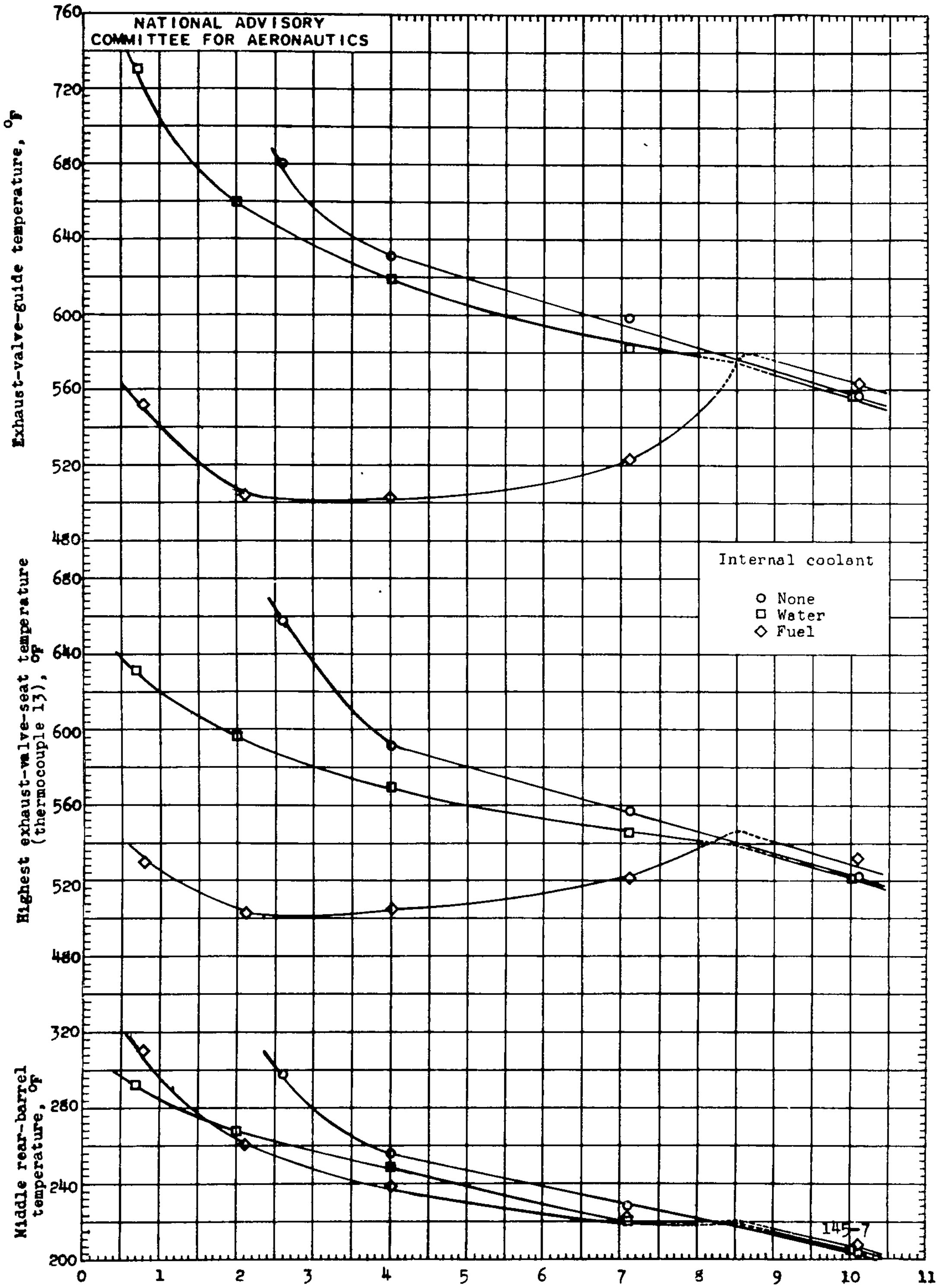


Figure 6. - Concluded. Effect of cooling-air pressure drop on performance of cylinder 1 equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spark-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.065; inlet-air pressure, 30 inches mercury absolute; inlet-air temperature, 150° F.

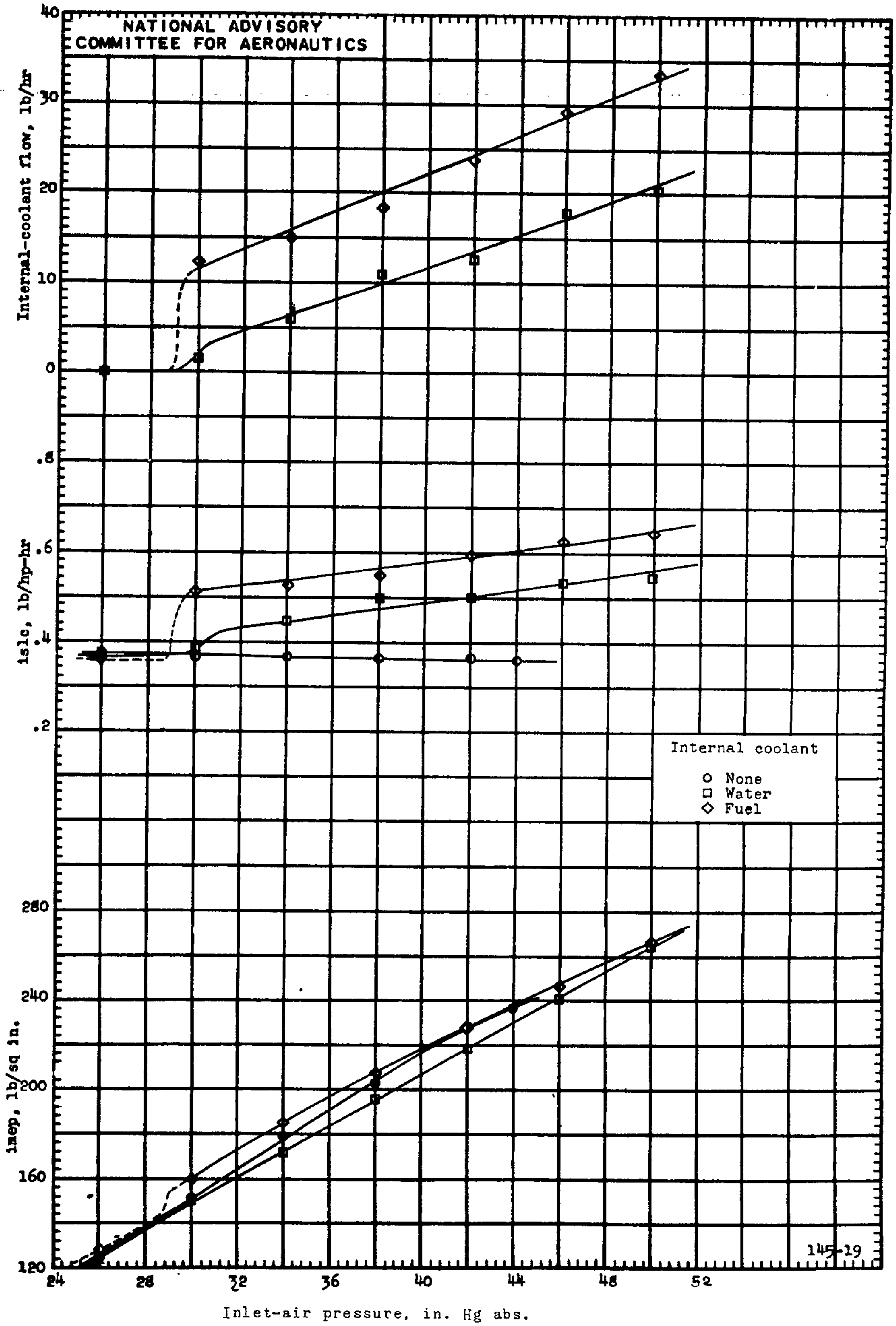


Figure 7. - Effect of inlet-air pressure on performance of cylinder I equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spar-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.065; inlet-air temperature, 150° F.

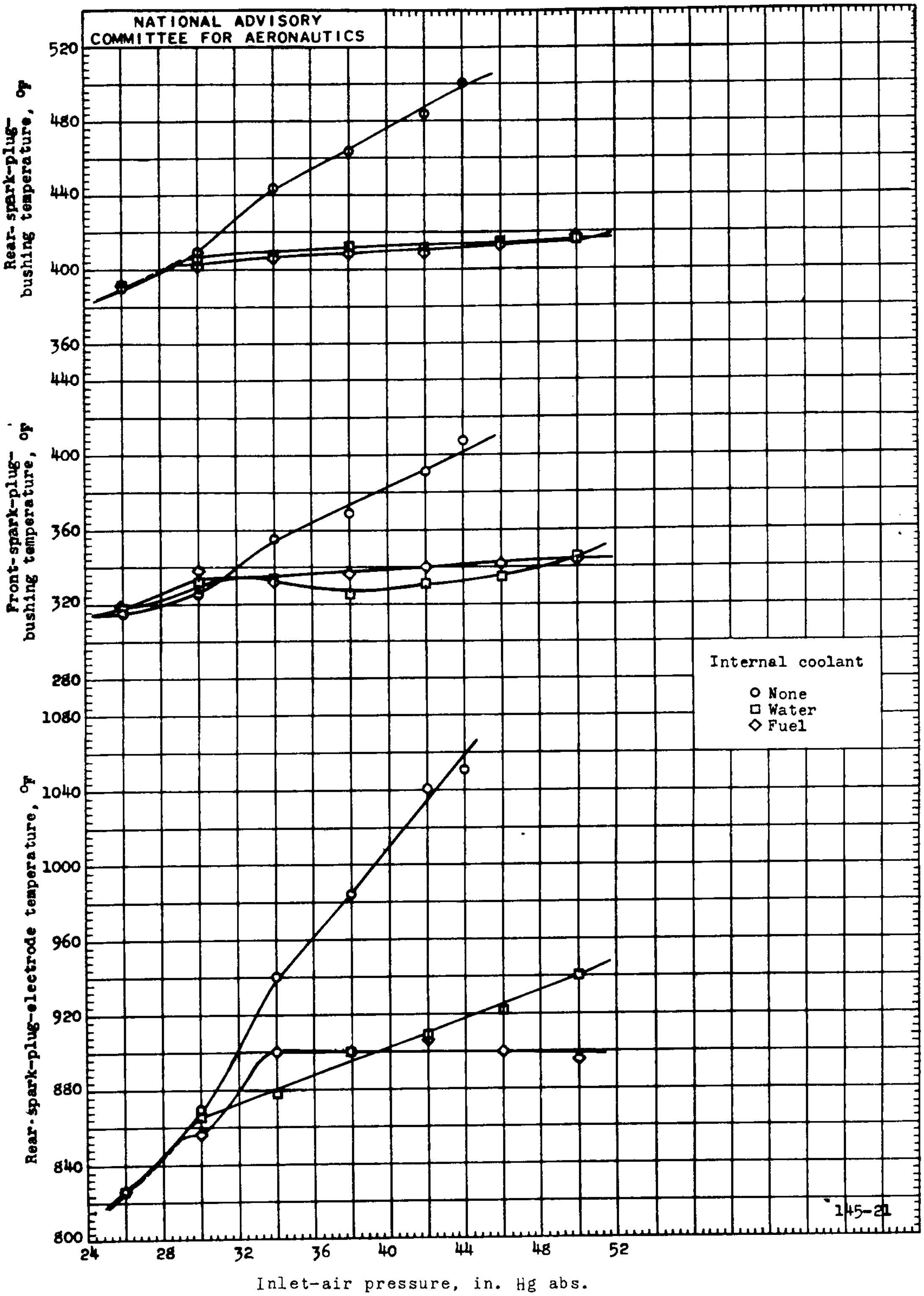


Figure 7. - Continued. Effect of inlet-air pressure on performance of cylinder I equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spark-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.065; inlet-air temperature, 150° F.

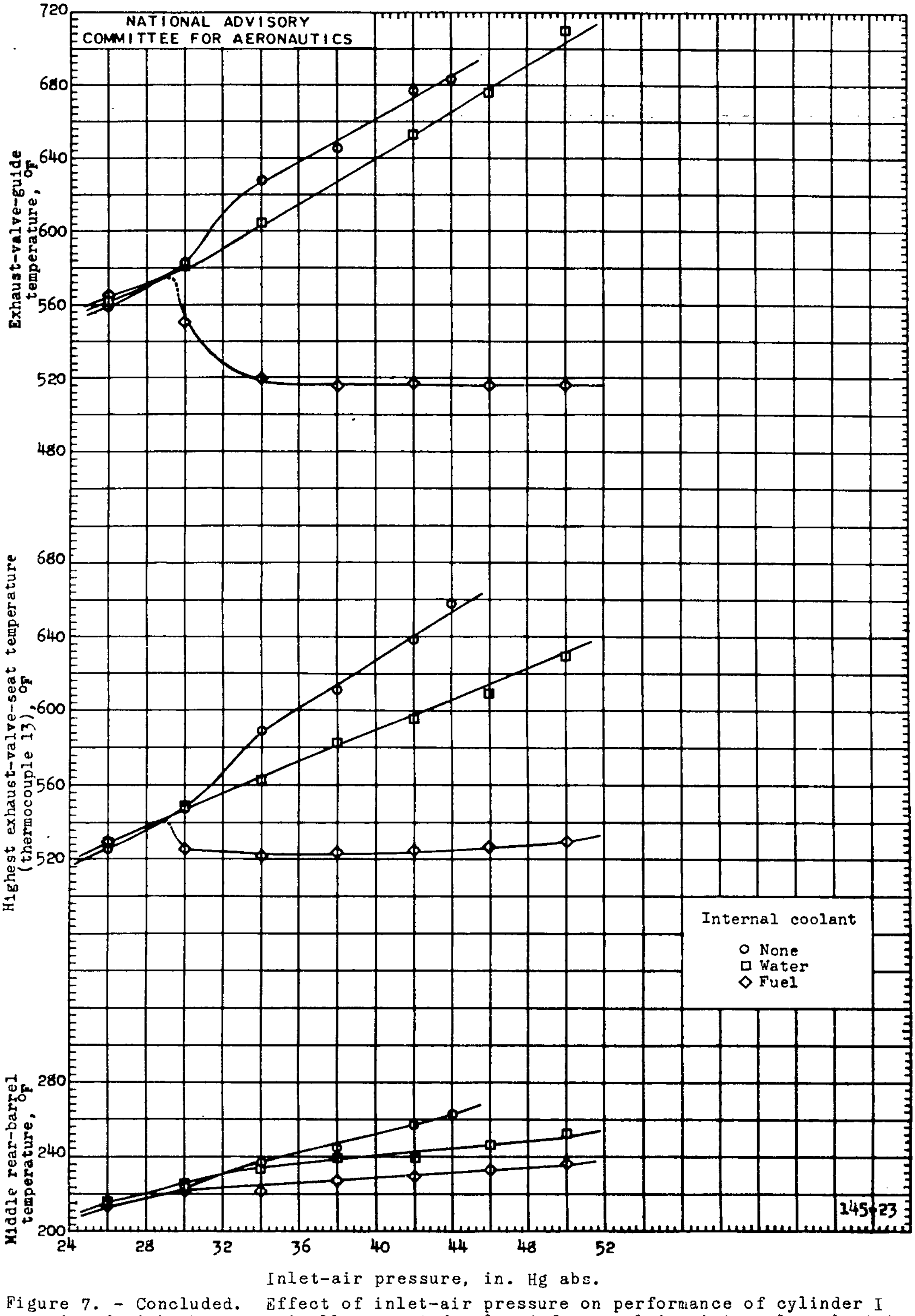
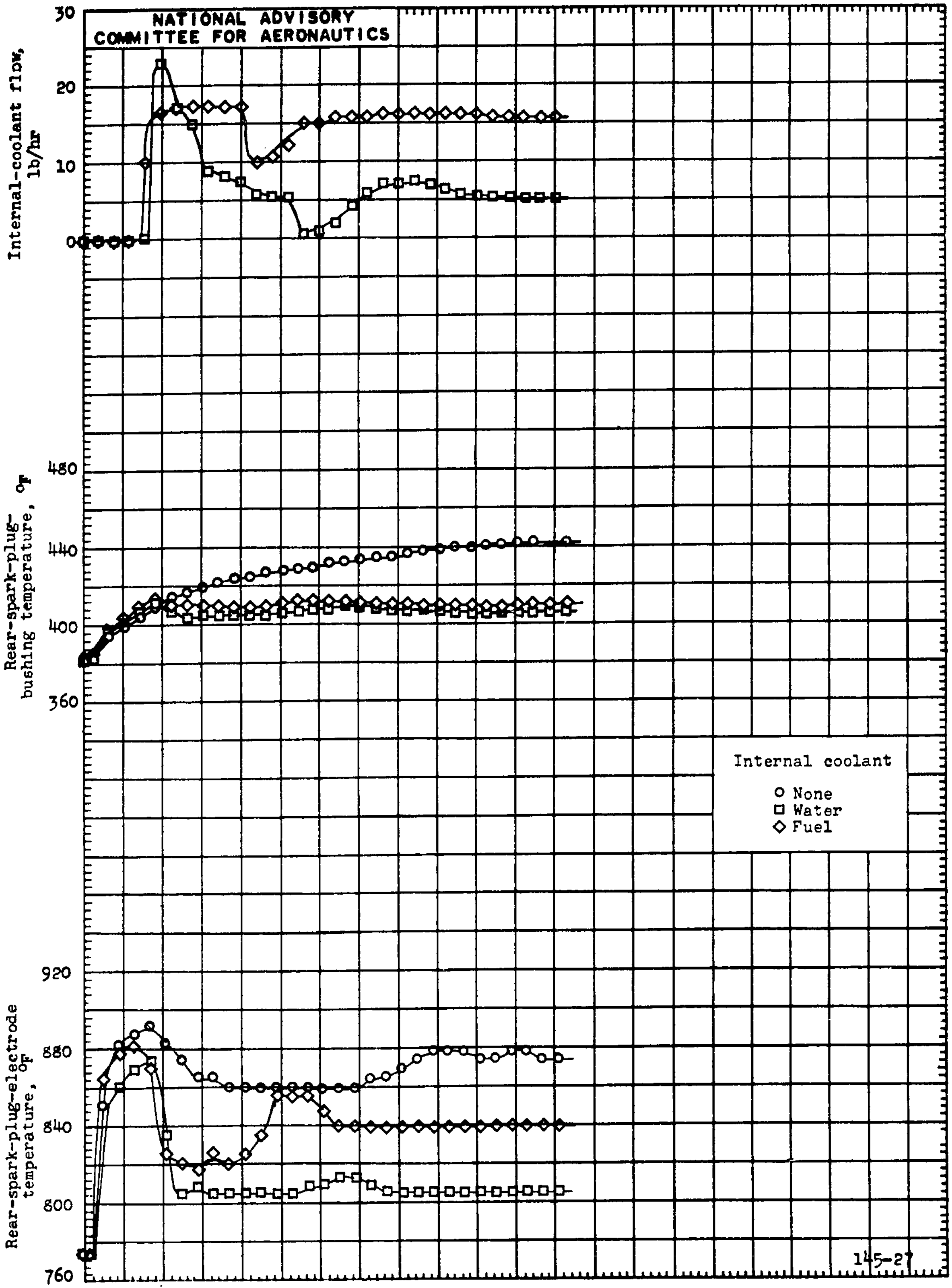


Figure 7. - Concluded. Effect of inlet-air pressure on performance of cylinder I equipped with thermostatically operated valve A for supplying internal coolant to maintain constant rear-spark-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.065; inlet-air temperature, 150° F.



Time after suddenly changing basic fuel-air ratio from 0.109 to 0.062, min

Figure 8. - Temperature change of cylinder I equipped with thermostatically operated valve A after a sudden reduction in basic fuel-air ratio from 0.109 to 0.062. Engine speed, 2000 rpm; inlet-air pressure, 30 inches mercury absolute; inlet-air temperature, 150° F; cooling-air pressure drop, 4.0 inches of water; coolant pressure, 2 pounds per square inch greater than inlet-air pressure.

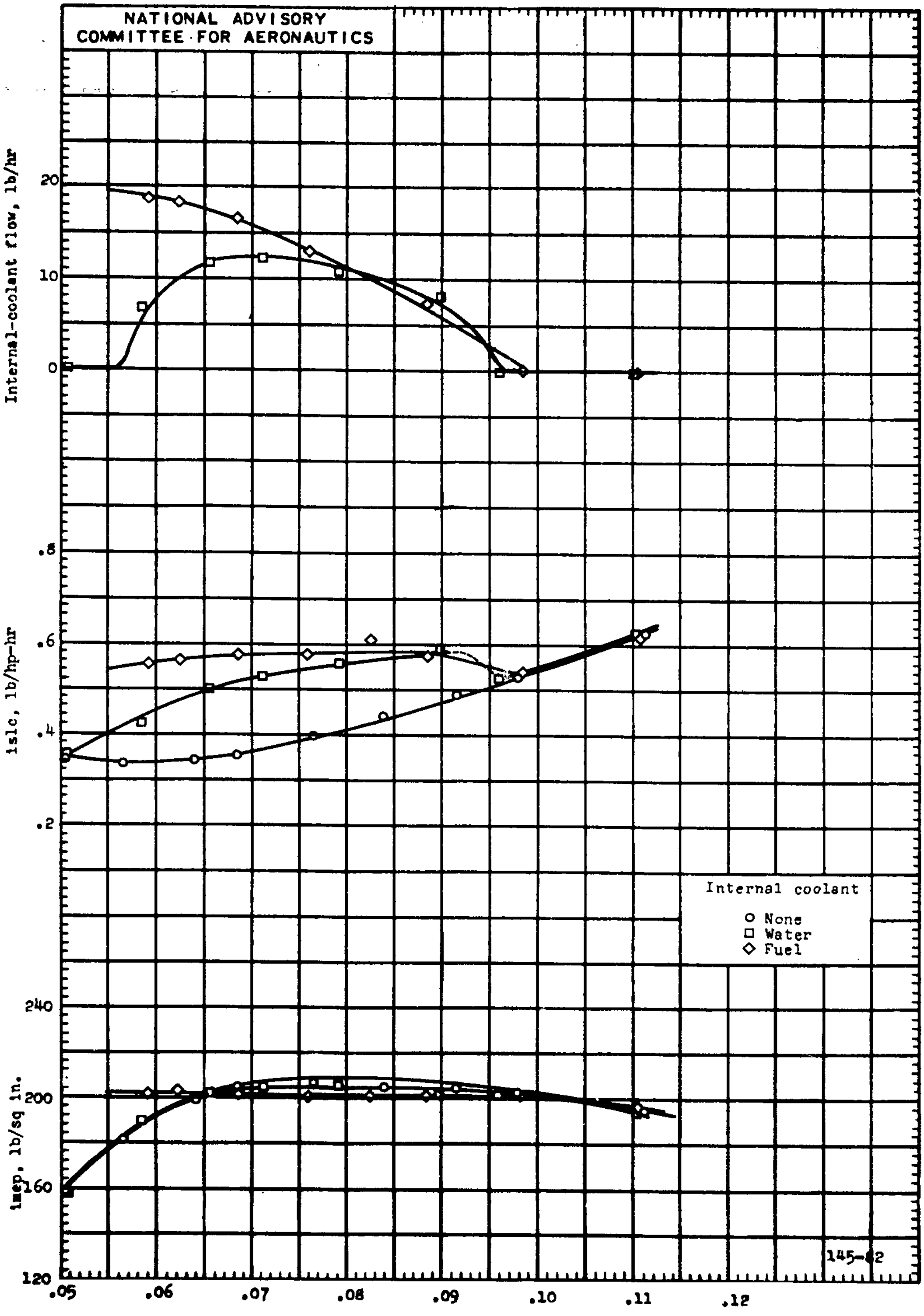


Figure 9. - Effect of basic fuel-air ratio on performance of cylinder II equipped with thermostatically operated valve B for supplying internal coolant to maintain constant front-spark-plug-bushing temperature. Engine speed, 2000 rpm; inlet-air pressure, 38 inches mercury absolute; inlet-air temperature, 150° F.

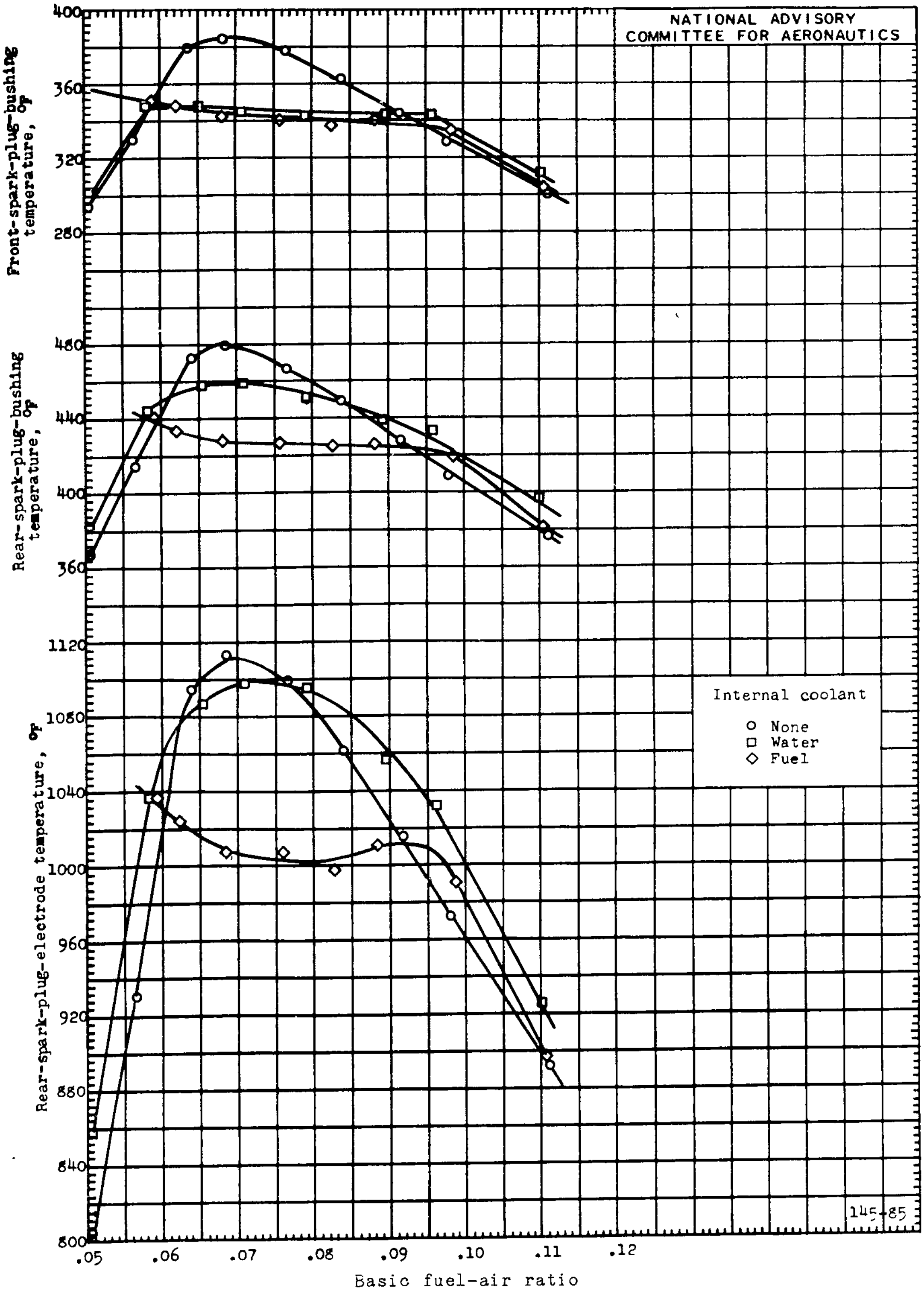


Figure 9. - Continued. Effect of basic fuel-air ratio on performance of cylinder II equipped with thermostatically operated valve B for supplying internal coolant to maintain constant front-spark-plug-busning temperature. Engine speed, 2000 rpm; inlet-air pressure, 38 inches mercury absolute; inlet-air temperature, 150° F.

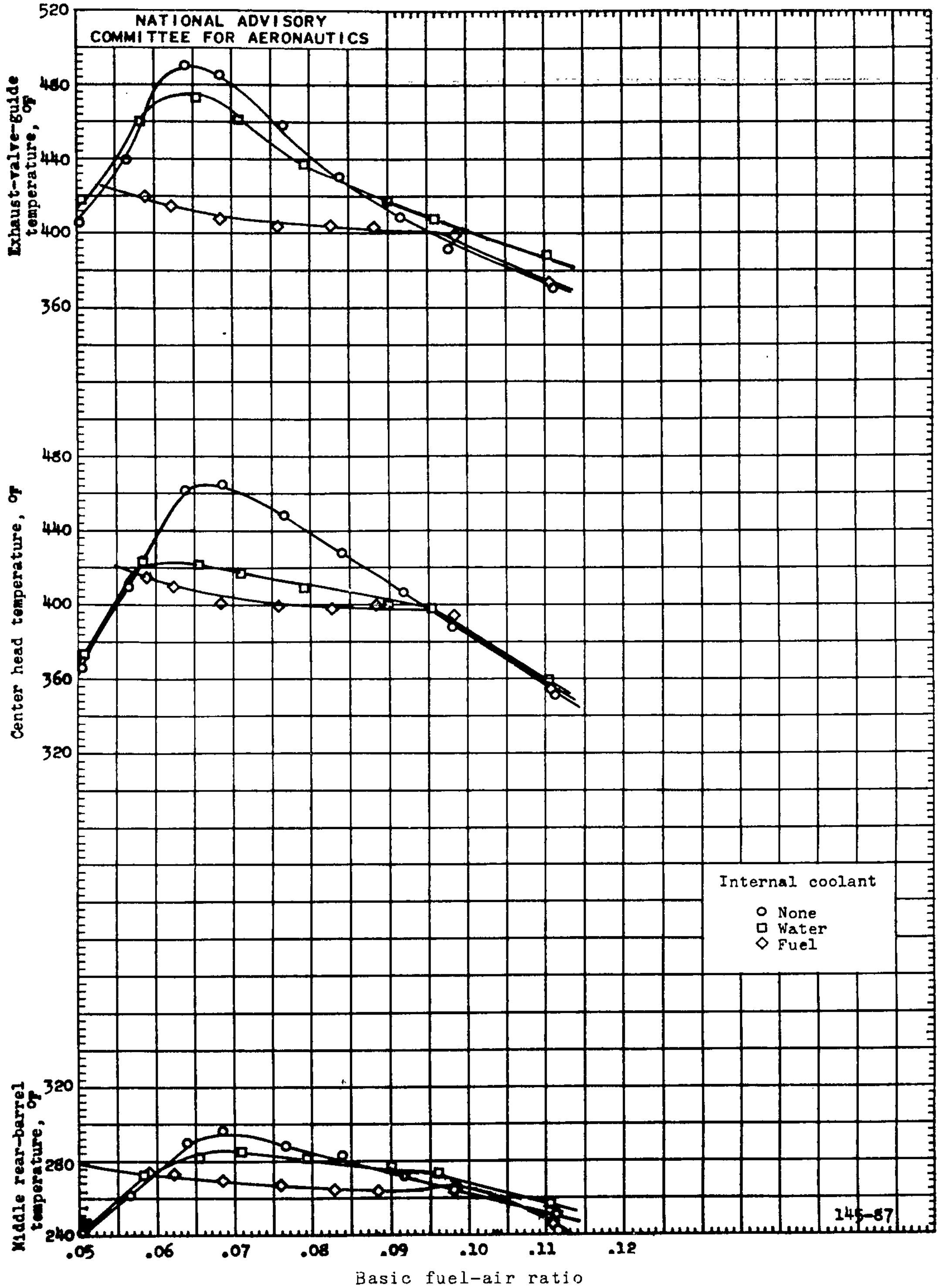


Figure 9. - Concluded. Effect of basic fuel-air ratio on performance of cylinder II equipped with thermostatically operated valve B for supplying internal coolant to maintain constant front-spark-plug-bushing temperature. Engine speed, 2000 rpm; inlet-air pressure, 38 inches mercury absolute; inlet-air temperature, 150° F.

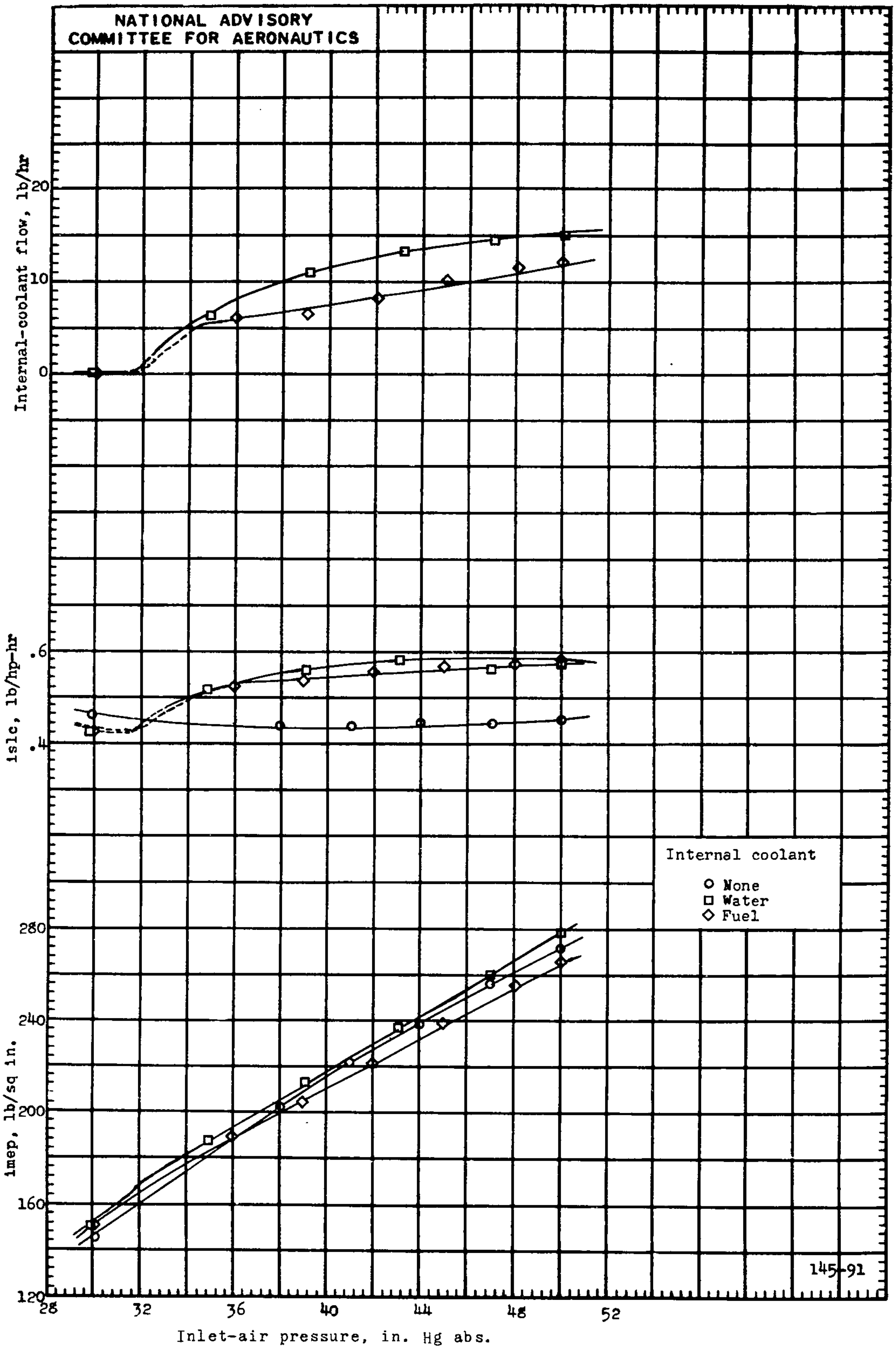


Figure 10. - Effect of inlet-air pressure on performance of cylinder II equipped with thermostatically operated valve B for supplying internal coolant to maintain constant front-spark-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.083; inlet-air temperature, 150° F.

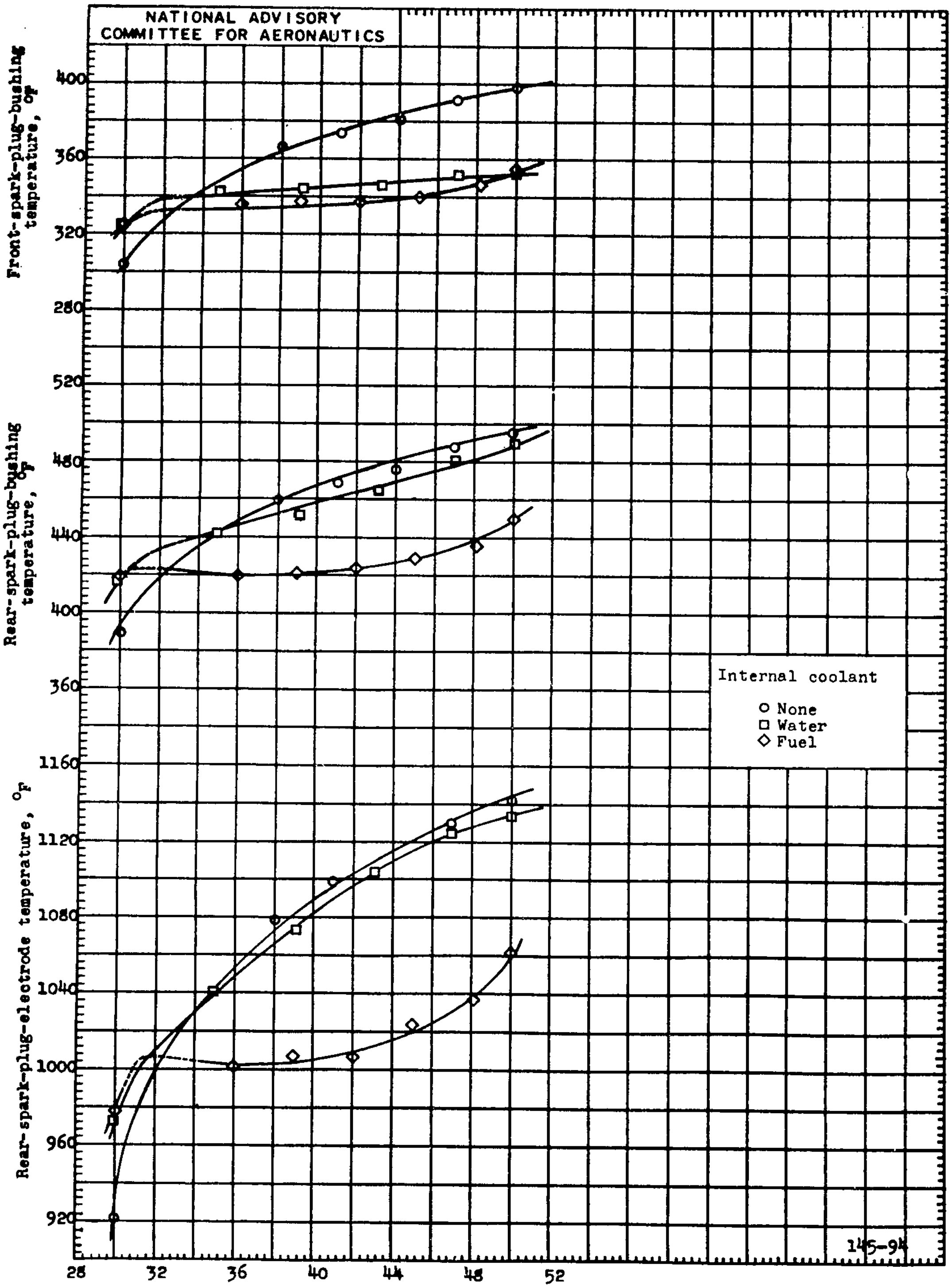


Figure 10. - Continued. Effect of inlet-air pressure on performance of cylinder II equipped with thermostatically operated valve B for supplying internal coolant to maintain constant front-spark-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.083; inlet-air temperature, 150° F.

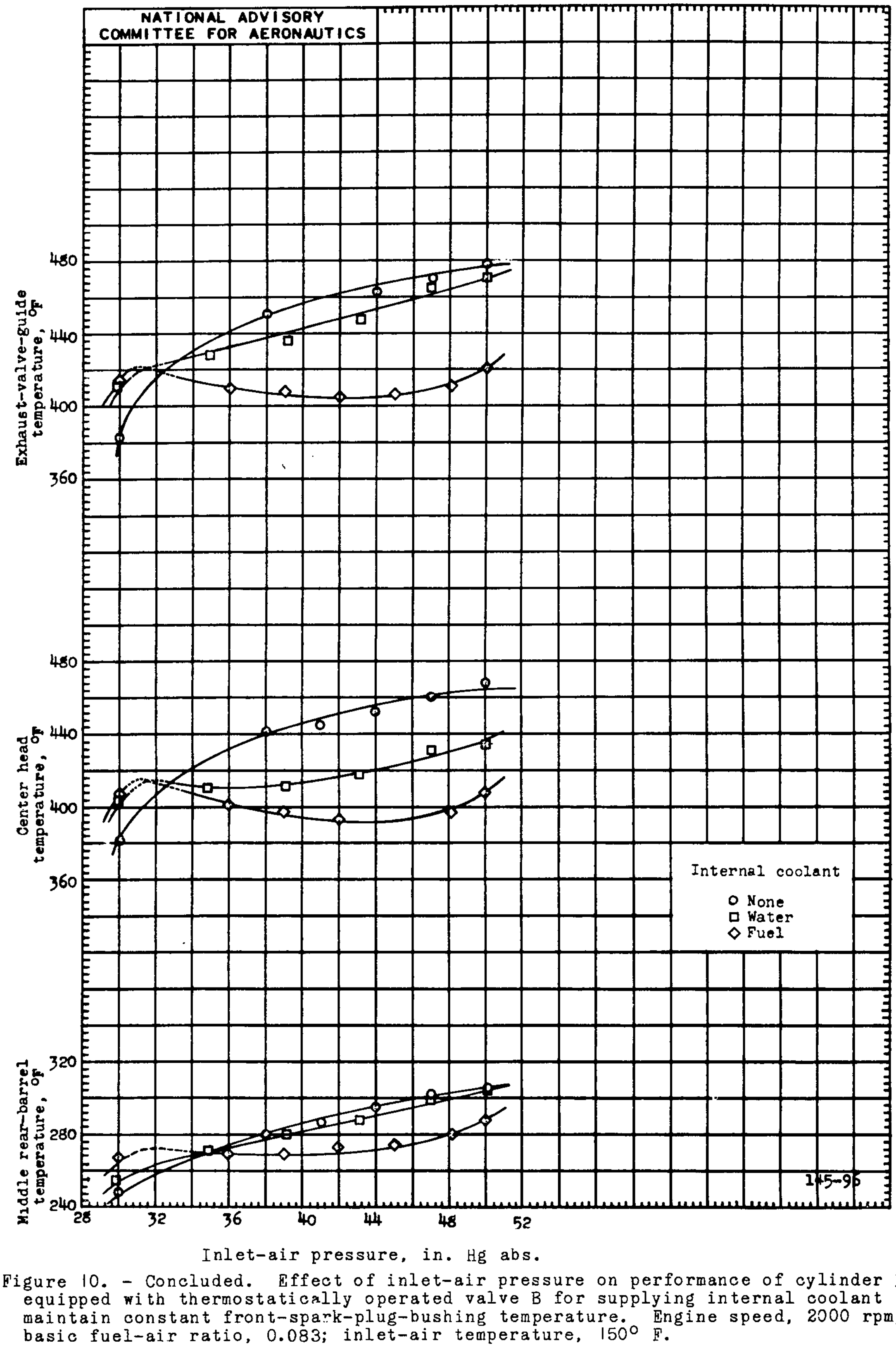
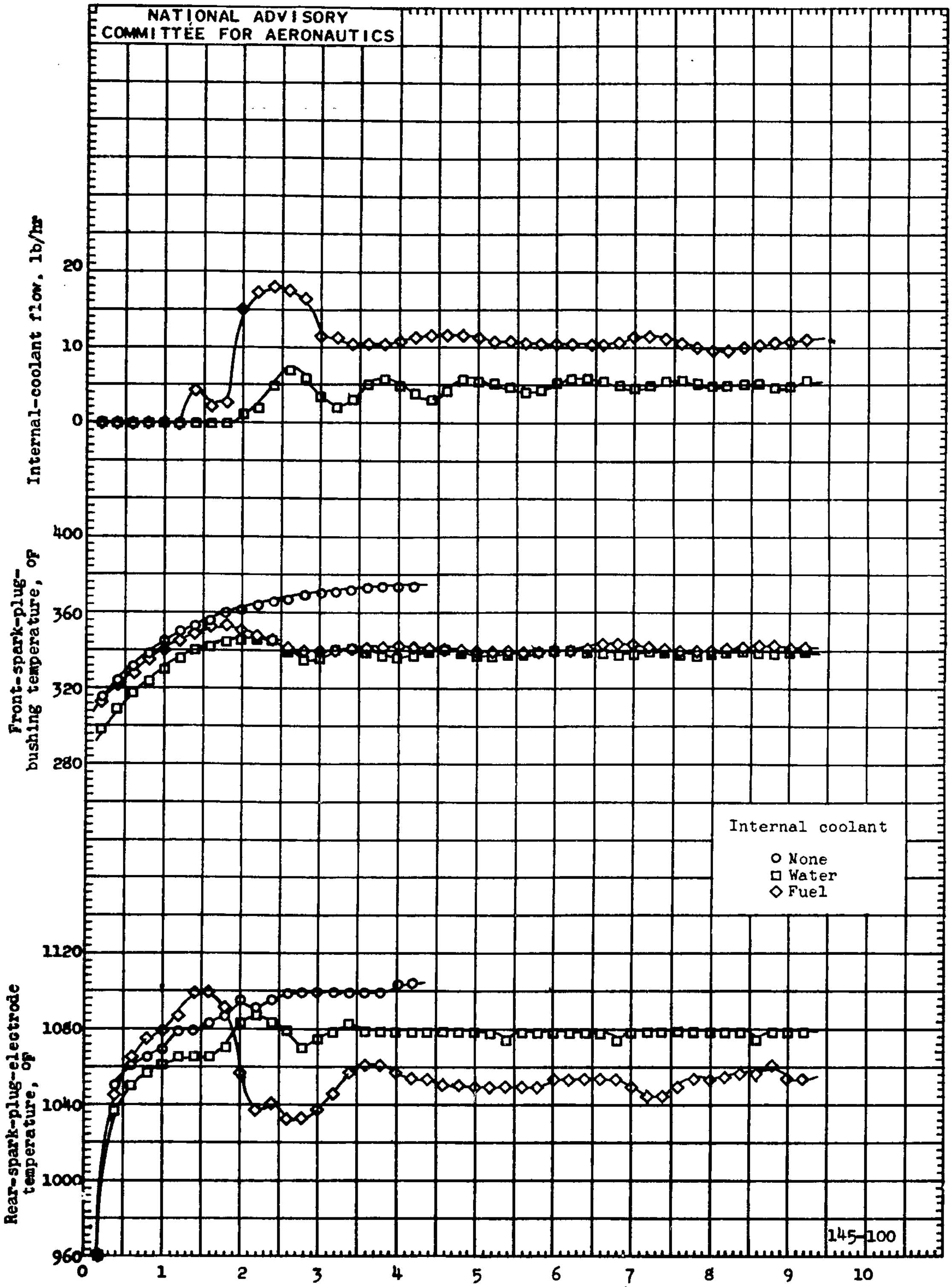


Figure 10. - Concluded. Effect of inlet-air pressure on performance of cylinder II equipped with thermostatically operated valve B for supplying internal coolant to maintain constant front-spark-plug-bushing temperature. Engine speed, 2000 rpm; basic fuel-air ratio, 0.083; inlet-air temperature, 150° F.



Time after suddenly changing basic fuel-air ratio from 0.100 to 0.065, min

Figure 11. - Temperature change of cylinder II equipped with thermostatically operated valve B after a sudden reduction in the basic fuel-air ratio from 0.100 to 0.065. Engine speed, 2000 rpm; inlet-air pressure, 38 inches mercury absolute; inlet-air temperature, 150° F; cooling-air pressure drop, 4.5 inches of water; coolant pressure, 2 pounds per square inch greater than inlet-air pressure.